Automatic Calculation of SUSY Particle Production and Decay with GRACE/SUSY-loop

Fujimoto, J., Ishikawa, T., Jimbo, M., Kon, T., Kurihara, Y.,
Kuroda, M. and Tomita, M.

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1. Introduction

- Automatic calculation of amplitudes

→ Important @ HE colliders LHC & ILC

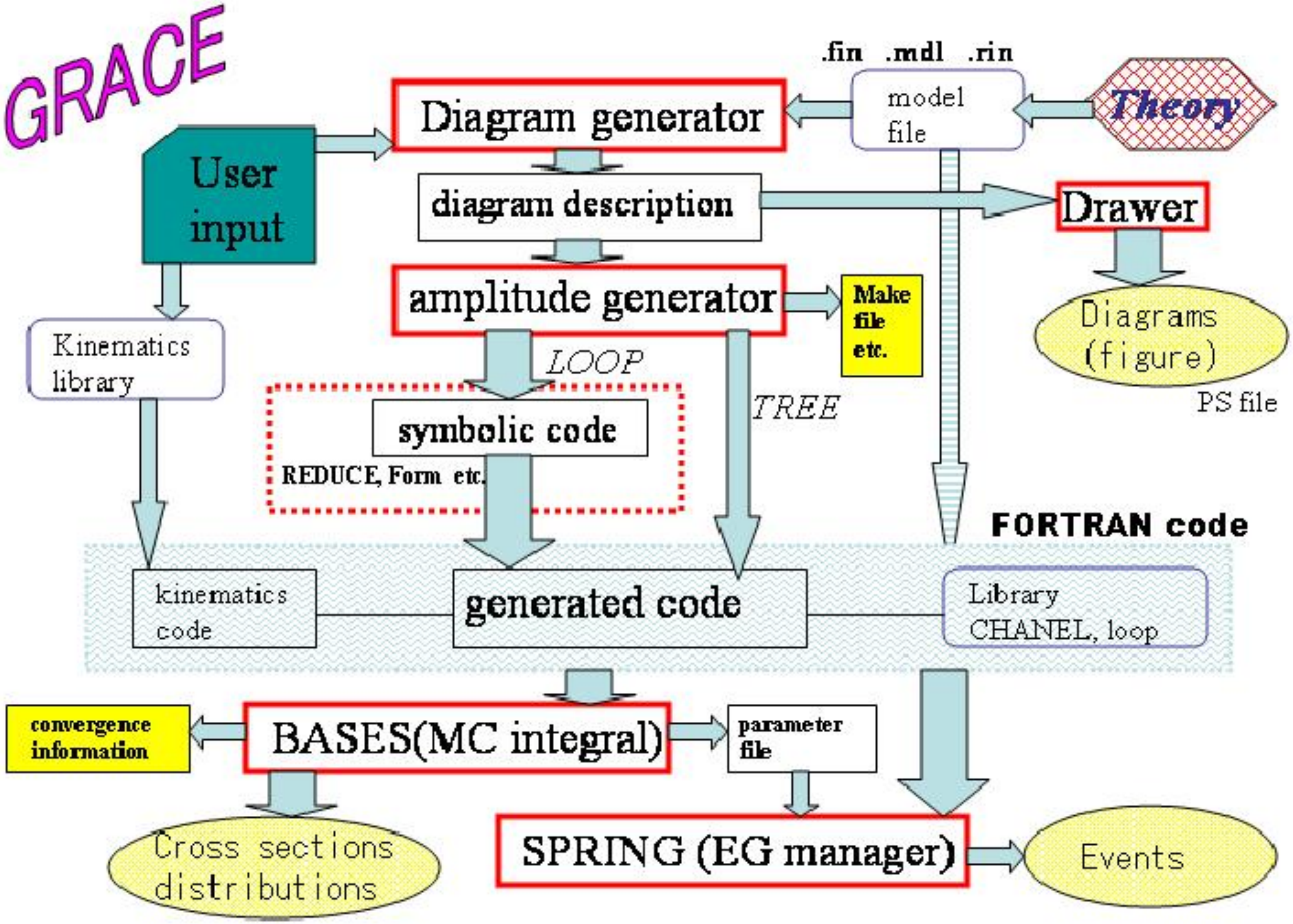
  - Many body final states
  - Possible many new particles

- Systems of automatic calculation

GRACE	Prog. Theor. Phys. Suppl. 138 (2000) 18
	Comput. Phys. Commun. 153 (2003) 106
CompHEP	Nucl. Instrum. Meth. A534 (2004) 250
CalcHEP	hep-ph/0412191
FeynArt/FormCalc	Comput.Phys.Commun. 140 (2001) 418;
	143 (2002) 54
MadGraph	JHEP 0302 (2003) 027

What we can do with GRACE

- ✓ Generate Feynman diagrams automatically
- ✓ Generate FORTRAN code of helicity amplitudes automatically (@ tree level)
- ✓ Generate symbolic (REDUCE, Form) source code for generating FORTRAN code of amplitudes automatically (@ one-loop level)
- ✓ Calculate phase-space integration of amplitudes numerically
- ✓ Generate events (unweighted)


GRACE
.fin .mdl .rin
Diagram generator
model file
Theory
User input
diagram description
Drawer
amplitude generator
Make file etc.
Diagrams (figure)
PS file
Kinematics library
LOOP
TREE
symbolic code
REDUCE, Form etc.
FORTRAN code
kinematics code
generated code
Library CHANEL, loop
convergence information
BASES(MC integral)
parameter file
Cross sections distributions
SPRING (EG manager)
Events

2. GRACE/SUSY & GRACE/SUSY-loop

- Tree level system ⇨ GRACE/SUSY

  COMPLETED!

  M. Kuroda, Complete Langarian of MSSM, hep-ph/9902340

  J. Fujimoto et al., Comput. Phys. Commun. 153 (2003) 106

  The system can be obtained at

  http://minami-home.kek.jp/

- One-loop level system

  ⇨ GRACE/SUSY-loop   Developing

  Renormailzation scheme;

  Physical results of chargino production and decay:

  J. Fujimoto et al., Phys. Rev. D75 (2007) 113002

Usage (GRACE/SUSY)

Input file 'in.prc'

```
Model="mssm.mdl";
Process;
  ELWK={3};
  Initial={electron positron};
  Final={photon neutralino1 neutralino2};
Kinem="2302";
Pend;
```

'grc'

Example

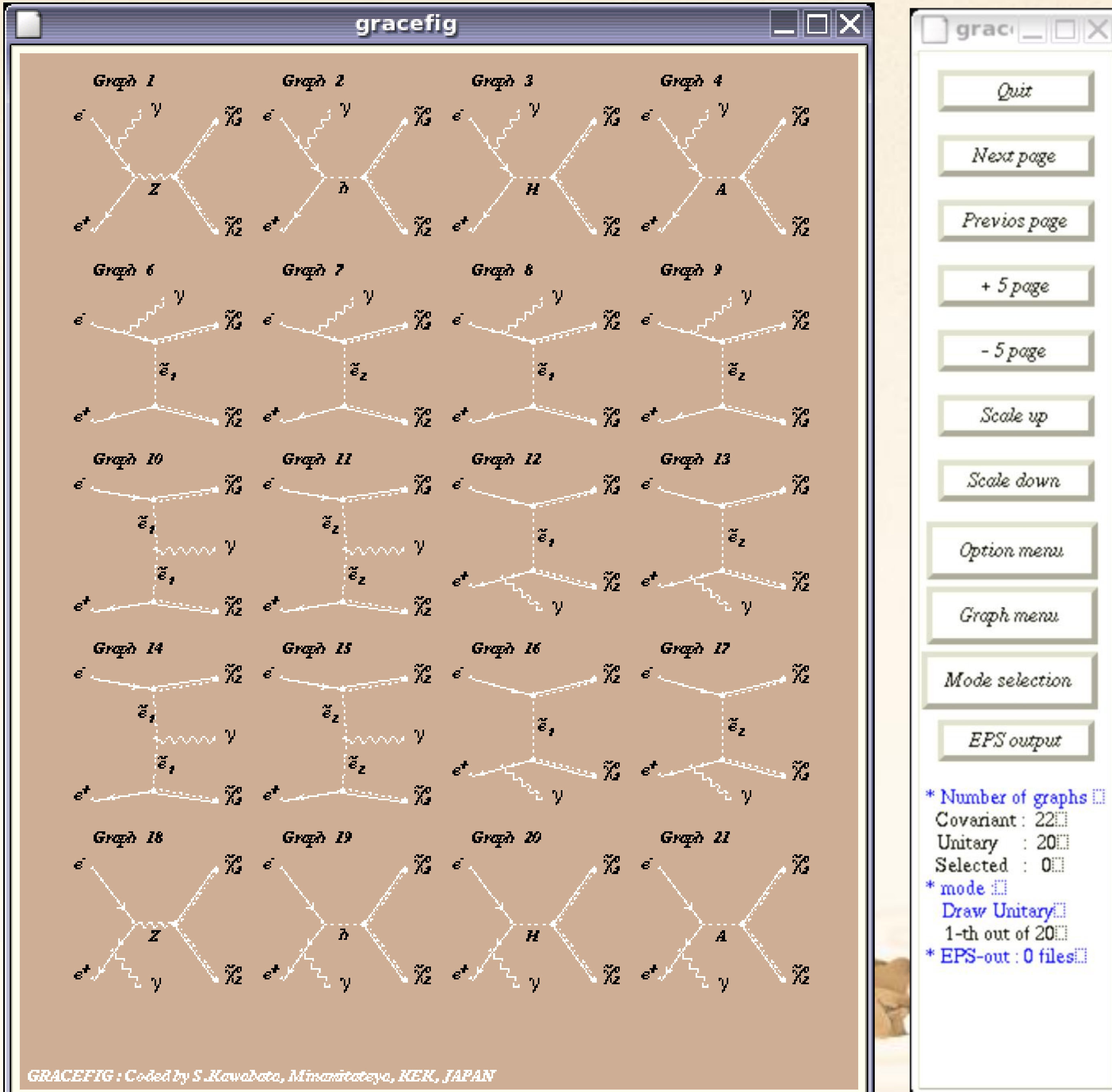
$$e^- \ e^+ \rightarrow \gamma \ \tilde{\chi}_1^0 \ \tilde{\chi}_2^0$$

Output file 'out.grf'

```
Graph=1;
Gtype=3;
Sfactor=1;
Vertex=3;
   0={    1[positron]};
   1={    2[electron]};
   2={    3[photon]};
   3={    4[neutralino1]};
   4={    5[neutralino2]};
   5[order={1,0,0}]={    1[electron],    3[photon],    6[positron]};
   6[order={1,0,0}]={    2[positron],    6[electron],    7[z]};
   7[order={1,0,0}]={    4[neutralino1],    5[neutralino2],    7[z]};
Vend;
Gend;
                              …
```

Feynman diagrams drawn by 'gracefig'

Fortran codes generated by 'grcfort'


gracefig
Graph 1
Graph 2
Graph 3
Graph 4
Graph 6
Graph 7
Graph 8
Graph 9
Graph 10
Graph 11
Graph 12
Graph 13
Graph 14
Graph 15
Graph 16
Graph 17
Graph 18
Graph 19
Graph 20
Graph 21
GRACEFIG : Coded by S.Kawabata, Minamitateya, KEK, JAPAN
Quit
Next page
Previos page
+ 5 page
- 5 page
Scale up
Scale down
Option menu
Graph menu
Mode selection
EPS output
* Number of graphs
Covariant : 22
Unitary : 20
Selected : 0
* mode :
Draw Unitary
1-th out of 20
* EPS-out : 0 files

Usage (GRACE/SUSY-loop)

Input file 'in.prc'

```
Model="mssmnlg_j2.mdl";
Process;
  ELWK={4,2};
  Initial={electron positron};
  Final={neutralino1 neutralino2};
  Expand=Yes; Block=No; AnyCT=No;
  Kinem="2201";
  ExtSelf=Mdl;
Pend;
```

↓ 'grc'

Output files for definition of Feynman diagrams

↓ 'grcred'

REDUCE source codes

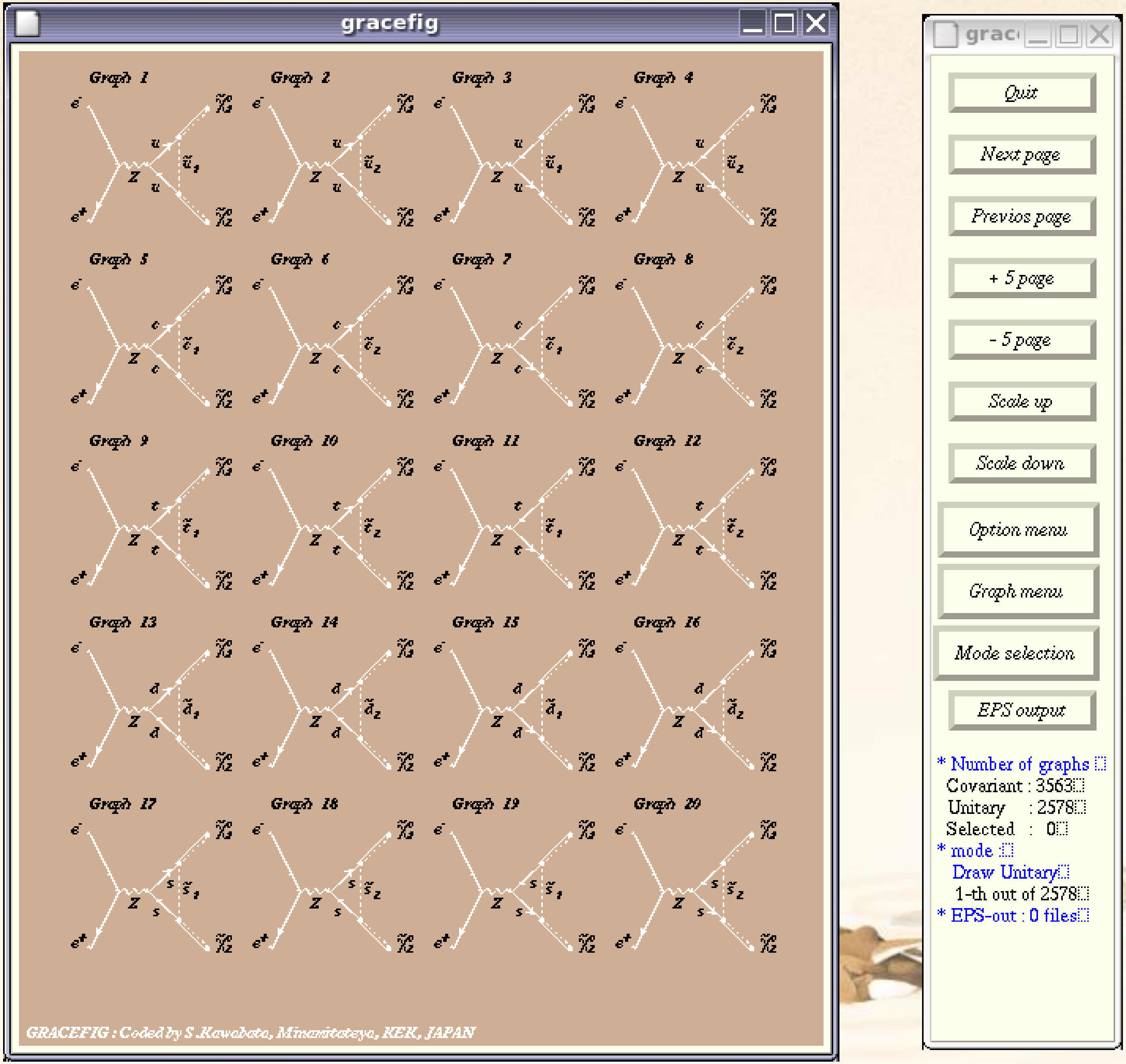
↓ 'make'

Fortran codes & Executable files

Example

$$e^- \ e^+ \rightarrow \tilde{\chi}_1^0 \ \tilde{\chi}_2^0$$

3554 one-loop level diagrams
9 tree-level diagrams


gracefig
Graph 1
Graph 2
Graph 3
Graph 4
Graph 5
Graph 6
Graph 7
Graph 8
Graph 9
Graph 10
Graph 11
Graph 12
Graph 13
Graph 14
Graph 15
Graph 16
Graph 17
Graph 18
Graph 19
Graph 20
GRACEFIG : Coded by S.Kawabata, Minamitateya, KEK, JAPAN
Quit
Next page
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+ 5 page
- 5 page
Scale up
Scale down
Option menu
Graph menu
Mode selection
EPS output
* Number of graphs
Covariant : 3563
Unitary : 2578
Selected : 0
* mode :
Draw Unitary
1-th out of 2578
* EPS-out : 0 files

Renormalization scheme

On-shell renormalization condition:

Gauge bosons, Fermions, Scalar fermions,
Higgs bosons (A^0, H^0), Neutralino ($\tilde{\chi}_1^0$),
Charginos ($\tilde{\chi}_1^+$, $\tilde{\chi}_2^+$)

Renormalization of tanβ:

$$\delta \tan\beta = -\frac{1}{2}\tan\beta\left(\delta Z_{H_1} - \delta Z_{H_2} - 2\frac{\delta v_1}{v_1} + 2\frac{\delta v_1}{v_1}\right)$$

Gauge invariance check with Non-linear gauge (NLG)!!

$$\frac{\delta v_1}{v_1} = \frac{\delta v_2}{v_2}$$ ➡ Gauge ↗

Renormalization of scalar fermions

1) Scheme Variation 1 (with SU(2) relation)

$$\delta m^2_{\tilde f} = -\mathrm{Re}\,\Sigma_{\tilde f \tilde f}(m^2_{\tilde f})$$

$$\delta m^2_{\tilde\nu_l} = 2\cos\theta_l \sin\theta_l \delta\theta_l (m^2_{\tilde l_2} - m^2_{\tilde l_1}) + \cos^2\theta_l \delta m^2_{\tilde l_1} + \sin^2\theta_l \delta m^2_{\tilde l_2}$$

$$+\delta(M_W^2 \cos 2\beta - m_l^2) \quad \Longrightarrow \quad \delta\theta_l$$

$$\delta\theta_u = \frac{1}{2}\frac{\Sigma_{\tilde u_1 \tilde u_2}(m^2_{\tilde u_2}) + \Sigma_{\tilde u_2 \tilde u_1}(m^2_{\tilde u_1})}{m^2_{\tilde u_2} - m^2_{\tilde u_1}}$$

$$\sin^2\theta_u \delta m^2_{\tilde u_2} = 2\cos\theta_d \sin\theta_d \delta\theta_d (m^2_{\tilde d_2} - m^2_{\tilde d_1}) + \cos^2\theta_d \delta m^2_{\tilde d_1}$$

$$+\sin^2\theta_d \delta m^2_{\tilde d_2} - 2\cos\theta_u \sin\theta_u \delta\theta_u (m^2_{\tilde u_2} - m^2_{\tilde u_1}) - \cos^2\theta_u \delta m^2_{\tilde u_1}$$

$$+\delta(M_W^2 \cos 2\beta + m_u^2 - m_d^2) \quad \Longrightarrow \quad \delta\theta_d$$

2) Scheme Variation 2

$$\delta m^2_{\tilde{f}} = -\mathrm{Re}\,\Sigma_{\tilde{f}\tilde{f}}(m^2_{\tilde{f}})$$

$$\delta\theta_e = \frac{1}{2}\frac{\Sigma_{\tilde{e}_1\tilde{e}_2}(m^2_{\tilde{e}_2}) + \Sigma_{\tilde{e}_2\tilde{e}_1}(m^2_{\tilde{e}_1})}{m^2_{\tilde{e}_2} - m^2_{\tilde{e}_1}}$$

$$\delta\theta_q = \frac{1}{2}\frac{\Sigma_{\tilde{q}_1\tilde{q}_2}(m^2_{\tilde{q}_2}) + \Sigma_{\tilde{q}_2\tilde{q}_1}(m^2_{\tilde{q}_1})}{m^2_{\tilde{q}_2} - m^2_{\tilde{q}_1}} \qquad q = u, d$$

Nonlinear gauge fixing terms in MSSM

$$F_{W^\pm} = (\partial_\mu \pm ie\tilde{\alpha}A_\mu \pm igc_W\tilde{\beta}Z_\mu)W^{\pm\mu}$$

$$\pm i\xi_W \frac{g}{2}(v + \tilde{\delta}_h h^0 + \tilde{\delta}_H H^0 \pm i\tilde{\kappa}G^0)G^\pm$$

$$F_Z = \partial_W Z^\mu + \xi_Z \frac{g_Z}{2}(v + \tilde{\varepsilon}_h h^0 + \tilde{\varepsilon}_H H^0)G^0$$

$$F_\gamma = \partial_\mu A^\mu$$

$(\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}_h, \tilde{\delta}_H, \tilde{\kappa}, \tilde{\varepsilon}_h, \tilde{\varepsilon}_H)$: NLG parameters

3. Physical results

- Neutralino production (one-loop level)

$$e^- e^+ \to \tilde{\chi}_1^0 \, \tilde{\chi}_2^0$$

Ref. Őller, W. et al., Phys. Lett. B590 (2004) 273; Phys. Rev. D71 (2005) 115002

Fritzsche, T. et al., Nucl. Phys. Proc. Suppl. 135 (2004) 102

- Neutralino decay (one-loop level)

$$\tilde{\chi}_2^0 \to 2\text{-body} \quad \tilde{\chi}_3^0 \to 2\text{-body} \quad \tilde{\chi}_4^0 \to 2\text{-body}$$

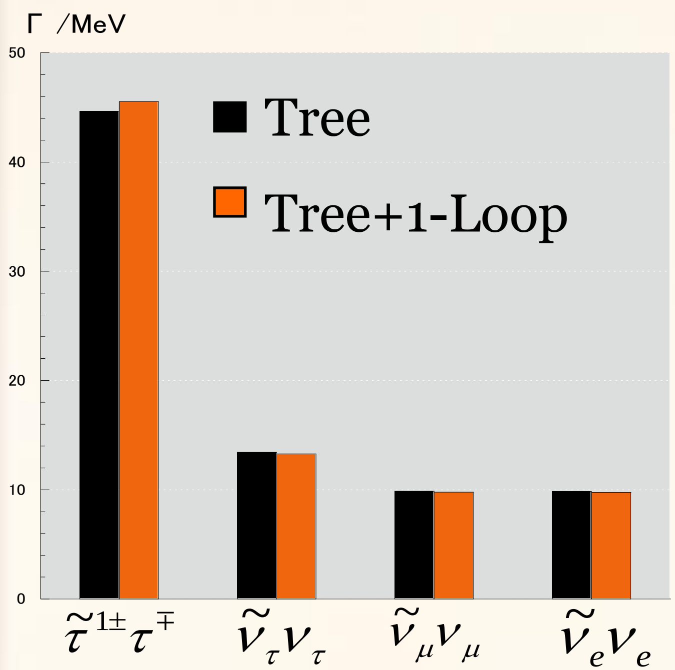
$$\tilde{\chi}_2^0 \to 3\text{-body}$$

Ref. Drees, M. et al., JHEP 0702 (2007) 032

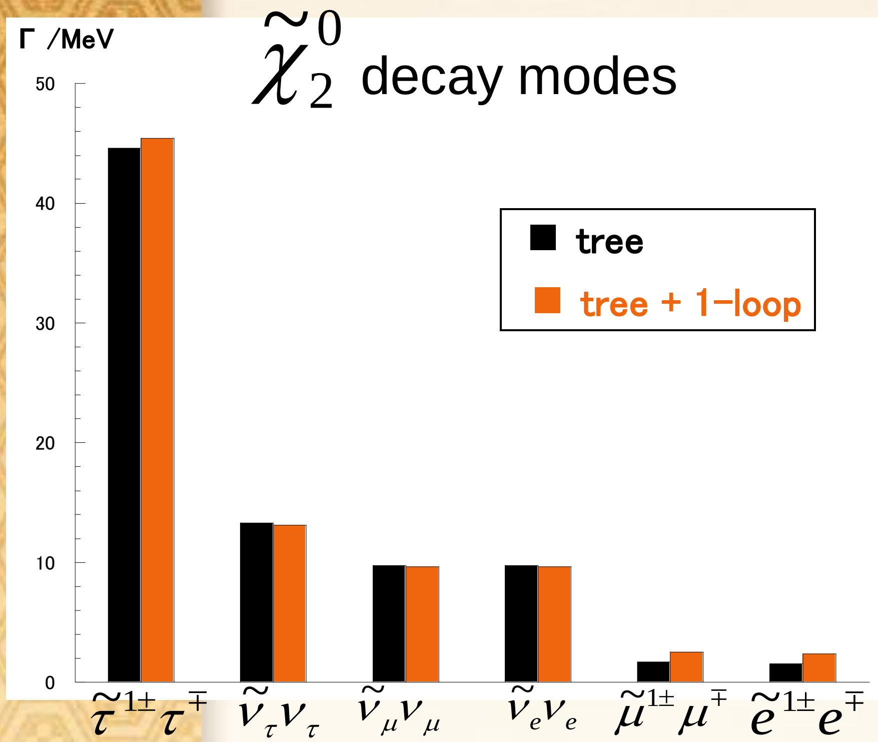
★ SPS1a' parameters: Aguilar-Saavedra, J. A. et al., Eur. Phys. J. C46 (2006) 43

2-body decay of $\tilde{\chi}_2^0$ SPS1a'

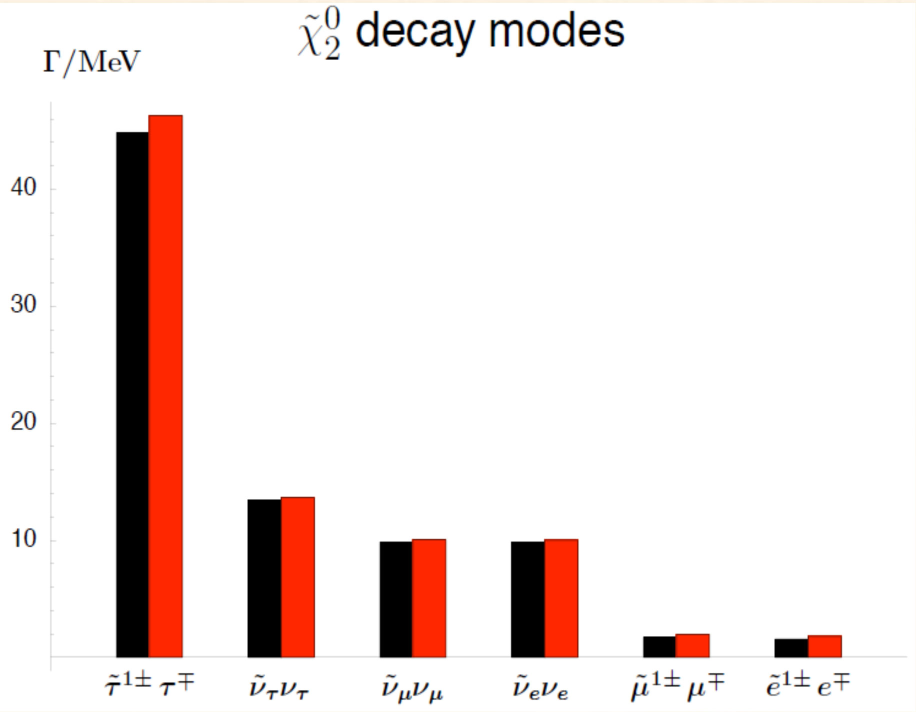
neutralino2 -->	#of 1-loop diagrams	Γ[Gev]	δ1loop	Γ+δΓ	Br_corr
anti-snu-tau, nu-tau	59	1.34E-02	-1.1%	1.33E-02	8.0%
anti-stau1, tau	98	4.47E-02	1.9%	4.55E-02	27.3%
anti-snu-mu, nu-mu	59	9.87E-03	-1.0%	9.77E-03	5.9%
anti-snu-e, nu-e	59	9.86E-03	-1.0%	9.75E-03	5.9%
nu-tau-bar, snu-tau	59	1.34E-02	-1.1%	1.33E-02	8.0%
anti-tau, stau1	98	4.47E-02	1.9%	4.55E-02	27.3%
nu-mu-bar, snu-mu	59	9.87E-03	-1.0%	9.77E-03	5.9%
nu-e-bar, snu-e	59	9.86E-03	-1.0%	9.75E-03	5.9%



One-loop correction with GRACE/SUSY and FeynArt/FeynCalc



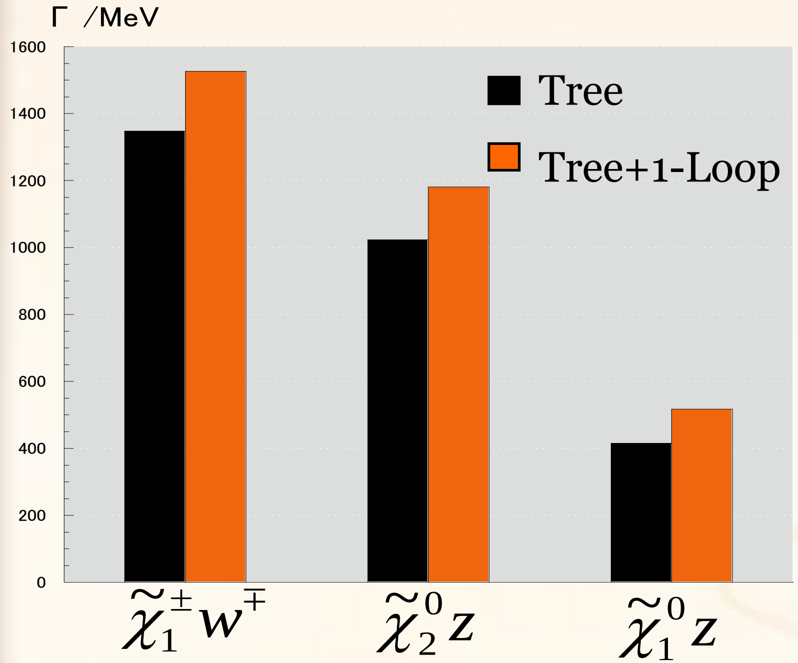
GRACE/SUSY



FeynArt/FeynCalc

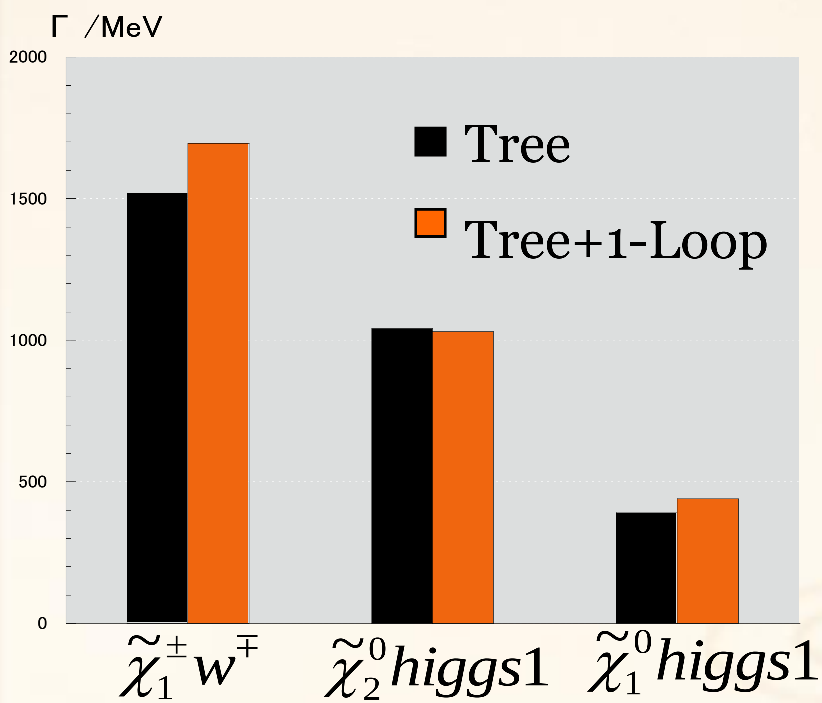
2-body decay of $\tilde{\chi}_3^0$ SPS1a'

neutralino3 -->	#of 1-loop diagrams	Γ[Gev]	δ1loop	Γ+δΓ	Br_corr
anti-chargino1, w-plus	193	1.35E+00	13.2%	1.53E+00	30.1%
chargino1, w-minus	193	1.35E+00	13.2%	1.53E+00	30.1%
z, neutralino1	304	4.15E-01	24.6%	5.17E-01	10.2%
z, neutralino2	304	1.02E+00	15.3%	1.18E+00	23.3%



2-body decay of $\tilde{\chi}_4^0$ SPS1a'

neutralino4 -->	#of 1-loop diagrams	Γ[Gev]	δ1loop	Γ+δΓ	Br_corr
anti-chargino1, w-plus	193	1.52E+00	11.6%	1.70E+00	27.8%
chargino1, w-minus	193	1.52E+00	11.6%	1.70E+00	27.8%
neutralino1, higgs1	317	3.90E-01	12.8%	4.40E-01	7.2%
neutralino2, higgs1	317	1.04E+00	-1.1%	1.03E+00	16.9%



One-loop corrections for 3-body decay

Another scenario: 2-body decays cannot occur

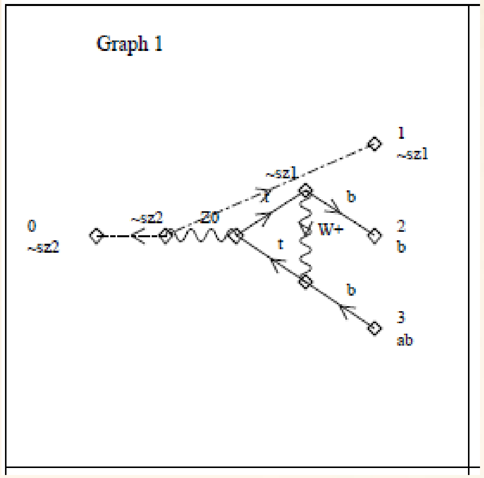
(with another parameter set)

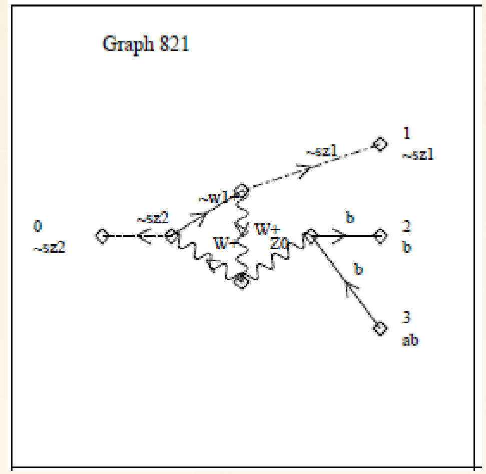
$\tilde{\chi}_2^0 \to$

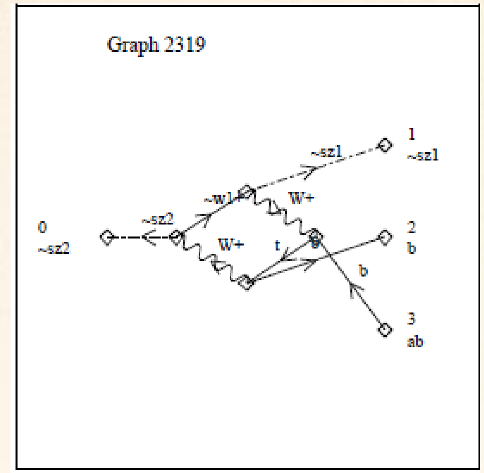
QCD one-loop		ELWK one-loop	
$\tilde{\chi}_1^0 u\bar{u}$	$\tilde{\chi}_1^0 s\bar{s}$	$\tilde{\chi}_1^0 \nu_e\bar{\nu}_e$	$\tilde{\chi}_1^0 e^- e^+$
$\tilde{\chi}_1^0 d\bar{d}$	$\tilde{\chi}_1^0 b\bar{b}$	$\tilde{\chi}_1^0 \nu_\mu\bar{\nu}_\mu$	$\tilde{\chi}_1^0 \mu^- \mu^+$
$\tilde{\chi}_1^0 c\bar{c}$		$\tilde{\chi}_1^0 \nu_\tau\bar{\nu}_\tau$	$\tilde{\chi}_1^0 \tau^- \tau^+$

Feynman diagrams of $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 b\bar{b}$

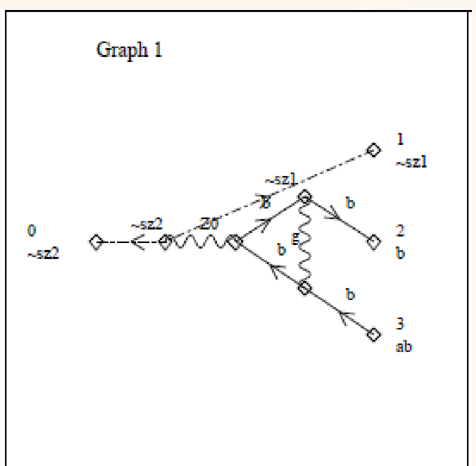
ELWK One-loop (3716 diagrams)

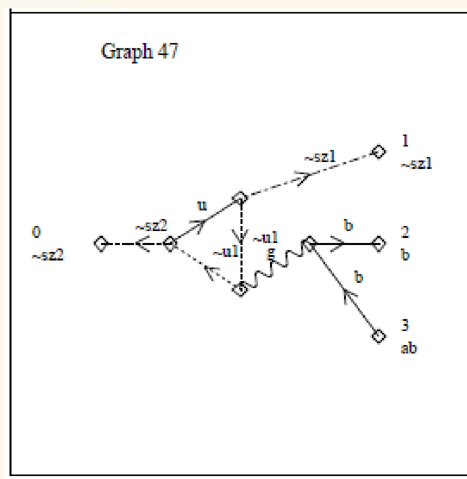


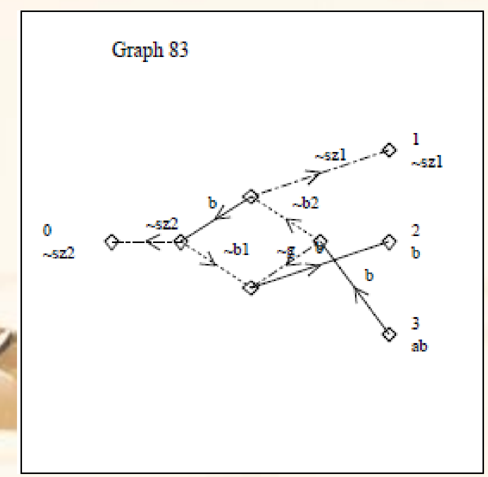




QCD One-loop (126 diagrams)



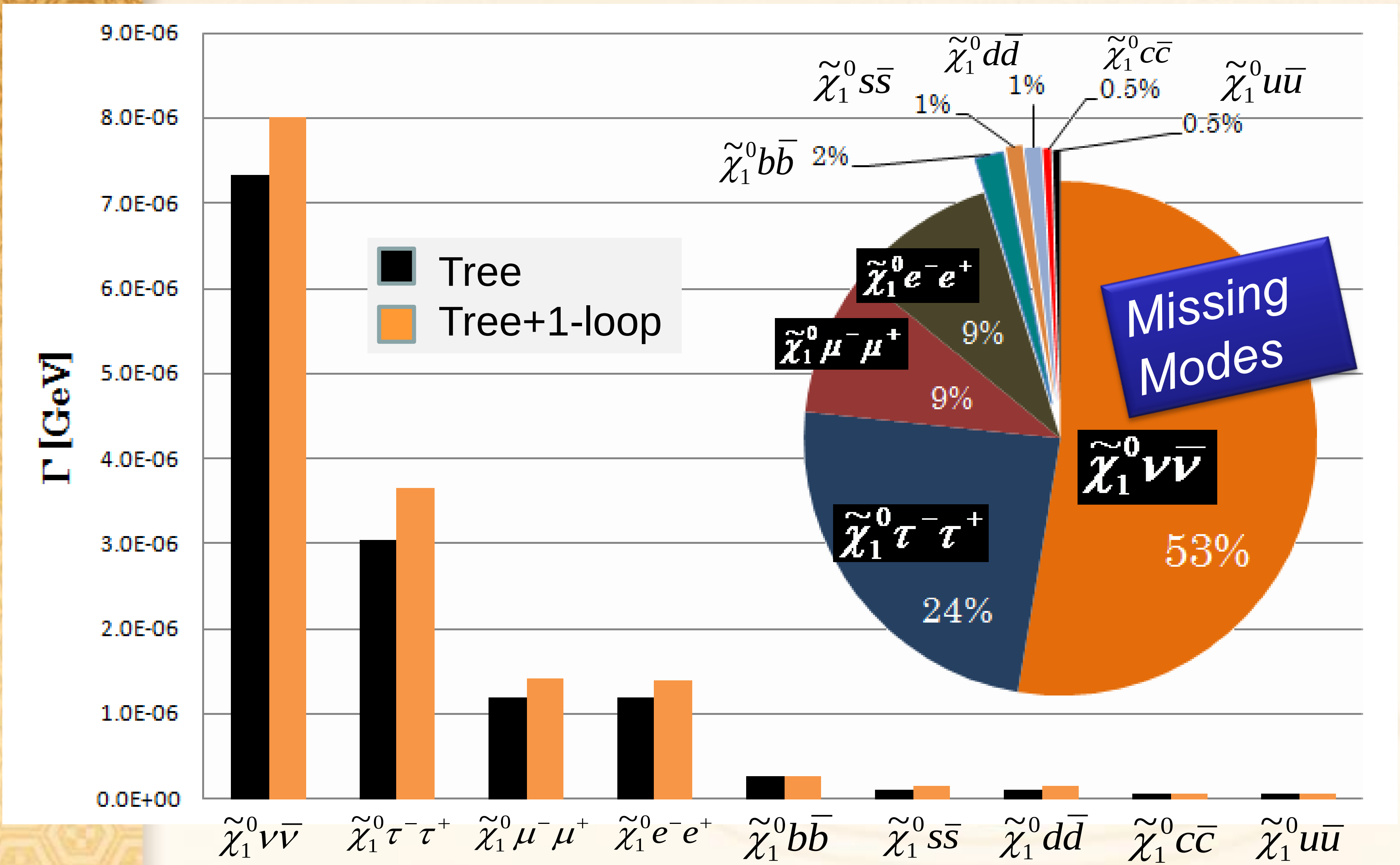




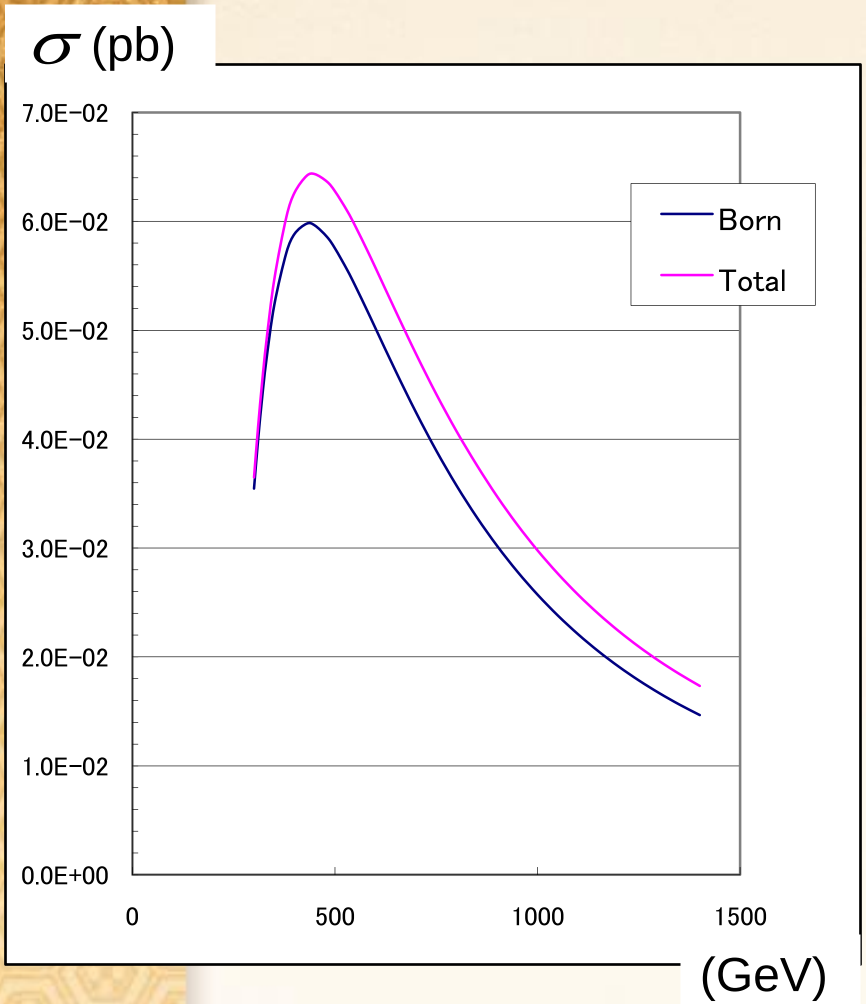
3-body decay of $\tilde{\chi}_2^0$

	neutralino2 -->	#of 1-loop diagram	Γ [Gev]	δ1loop	δ1loop	Γ+δΓ	Br_corr
1	neutralino1, nu-tau-bar,nu-tau	1112	2.412E-06	9.4%	9.4%	2.64E-06	17.3%
2	neutralino1, anti-tau, tau	3554	3.039E-06	20.2%	20.2%	3.65E-06	24.0%
3	neutralino1, nu-mu-bar, nu-mu	1112	2.457E-06	9.4%	9.4%	2.69E-06	17.7%
4	neutralino1, anti-muon, muon	3554	1.198E-06	17.7%	17.7%	1.41E-06	9.3%
5	neutralino1, nu-e-bar, nu-e	1112	2.458E-06	9.4%	9.4%	2.69E-06	17.7%
6	neutralino1, e+, e-	3554	1.196E-06	17.8%	17.8%	1.41E-06	9.3%
7	neutralino1, b-bar, b	3716 QCD:126	2.717E-07	1.5% -2.3%	-0.8%	2.70E-07	1.8%
8	neutralino1, s-bar, s	3716 QCD:126	1.218E-07	21.6% 7.7%	29.3%	1.57E-07	1.0%
9	neutralino1, c-bar, c	3716 QCD:126	6.727E-08	13.8% 1.8%	15.6%	7.78E-08	0.5%
10	neutralino1, d-bar, d	3716 QCD:126	1.217E-07	22.7% 7.8%	30.5%	1.59E-07	1.0%
11	neutralino1, u-bar, u	3716 QCD:126	6.156E-08	11.9% 4.8%	16.7%	7.18E-08	0.5%

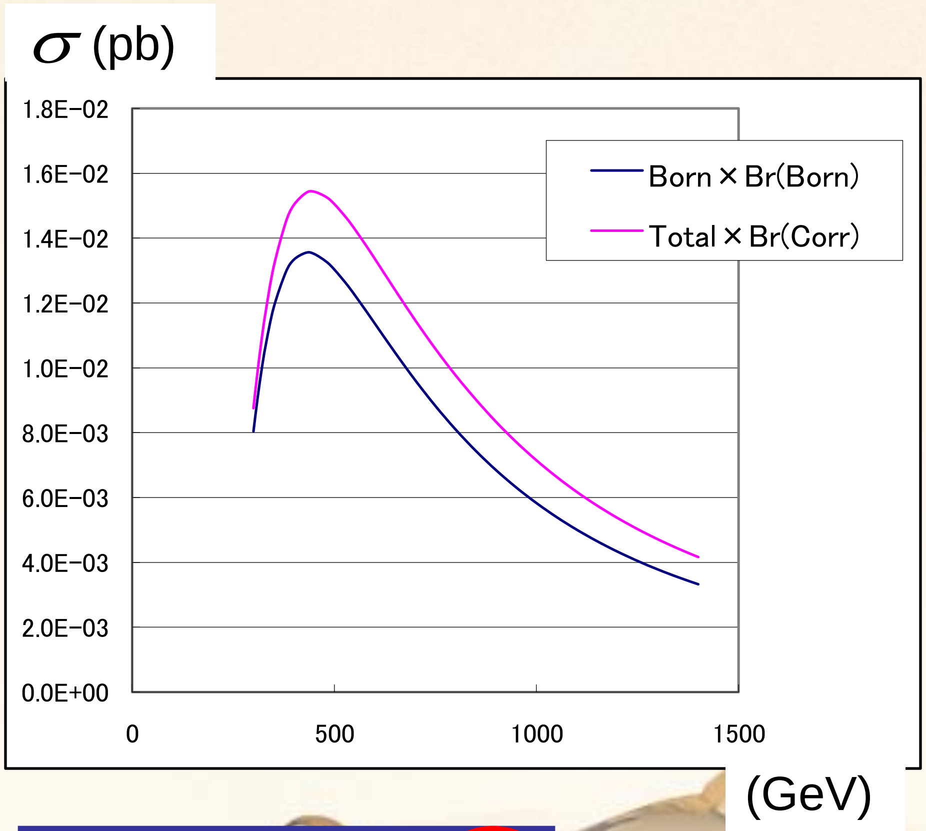
3-body decay of $\tilde{\chi}_2^0$



Production and decay of $\tilde{\chi}_2^0$



$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$$



$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$$

$$\to \tilde{\chi}_1^0 \tau^- \tau^+$$

How to check results

$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$$

For σ [(Full loop-diagrams)×(A tree-diagram)]

Gauge invariance check (NLG)

31 digits

- $(\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}_h, \tilde{\delta}_H, \tilde{\kappa}, \tilde{\varepsilon}_h, \tilde{\varepsilon}_H) = (0,0,0,0,0,0,0)$

σ (Virtual) = -1.972987938581775280094625099846939 5E-02

- $(\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}_h, \tilde{\delta}_H, \tilde{\kappa}, \tilde{\varepsilon}_h, \tilde{\varepsilon}_H) = (1,2,3,4,5,6,7)$

σ (Virtual) = -1.9729879385817752800946250998462461E-02

Ultraviolet check (CUV)

22 digits

- CUV = 0

σ (Virtual) = -1.9729879385817752800946250998469395E-02

- CUV = 1000

σ (Virtual) = -1.9729879385817752800947890626998724E-02

For σ [(Selected loop-diagrams)×(All tree-diagrams)]
[ommitted e-e-scalar vertices]

Fictitious photon mass (λ)

- λ = 1.0E-24

  σ(Virtual+Soft) = -3.95636186320988E-2
- λ = 1.0E-27

  σ(Virtual+Soft) = -3.95636186322991E-2

Cut off photon energy (k_C)

[Hard photon: MC]

- k_C = 1.0E-3

  (Virtual+Soft+Hard) = 2.97876E-2
- k_C = 1.0E-1

  (Virtual+Soft+Hard) = 2.97886E-2

4. Summary

- GRACE/SUSY-loop
  - Powerful tool for SUSY RC analysis
    - Automatic calculation at one-loop level
      - EW and QCD in MSSM
    - Systematic studies for consistency check
      - Nonlinear gauge
      - C_{uv} check, Infrared check, etc.
  - Now, up to 2⟶2 and 1⟶3 processes have been calculated

Parameters set: SPS1a'

mSUGRA values

$M_{1/2} = 250\text{GeV}$ $\quad sign(\mu) = +1$

$M_0 = 70\text{GeV}$ $\quad tan\beta = 10$

$A_0 = -300\text{GeV}$

Low energy inputs

$M_1 = 100.1\text{GeV}$ $\quad m\nu_e = 0.0\text{GeV}$ $\quad mu = 58.0\times10^{-3}\text{GeV}$

$M_2 = 197.5\text{GeV}$ $\quad m\nu_\mu = 0.0\text{GeV}$ $\quad md = 58.0\times10^{-3}\text{GeV}$

$\mu = 399.2\text{GeV}$ $\quad m\nu_\tau = 0.0\text{GeV}$ $\quad mc = 1.5\text{GeV}$

$\tan\beta = 10$ $\quad me = 0.5109906\times10^{-3}\text{GeV}$ $\quad ms = 92.0\times10^{-3}\text{GeV}$

$M_{W^\pm} = 80.35\text{GeV}$ $\quad m\mu = 105.658389\times10^{-3}\text{GeV}$ $\quad mt = 178.0\text{GeV}$

$M_{z^0} = 91.187\text{GeV}$ $\quad m\tau = 1.7771GeV$ $\quad mb = 4.70\text{GeV}$

Sleptons

$m\tilde{e}_1 = 125.50\text{GeV}$

$m\tilde{e}_2 = 190.14\text{GeV}$

$\theta_e = 0.50\pi$

$m\tilde{\nu}_e = 172.70\text{GeV}$

$m\tilde{\mu}_1 = 125.43\text{GeV}$

$m\tilde{\mu}_2 = 190.16\text{GeV}$

$\theta_\mu = 0.49\pi$

$m\tilde{\nu}_\mu = 172.69\text{GeV}$

$m\tilde{\tau}_1 = 107.71\text{GeV}$

$m\tilde{\tau}_2 = 195.08\text{GeV}$

$\theta_\tau = 0.40\pi$

$m\tilde{\nu}_\tau = 170.63\text{GeV}$

Squarks

$m\tilde{u}_1 = 545.67\text{GeV}$

$m\tilde{u}_2 = 563.44\text{GeV}$

$\theta_u = 0.50\pi$

$m\tilde{d}_1 = 545.50\text{GeV}$

$m\tilde{d}_2 = 569.03\text{GeV}$

$\theta_d = 0.50\pi$

$m\tilde{s}_1 = 545.52\text{GeV}$

$m\tilde{s}_2 = 568.97\text{GeV}$

$\theta_s = 0.49\pi$

$m\tilde{c}_1 = 545.66\text{GeV}$

$m\tilde{c}_2 = 563.45\text{GeV}$

$\theta_c = 0.48\pi$

$m\tilde{t}_1 = 368.53\text{GeV}$

$m\tilde{t}_2 = 583.79\text{GeV}$

$\theta_t = 0.24\pi$

$m\tilde{b}_1 = 450.12\text{GeV}$

$m\tilde{b}_2 = 544.38\text{GeV}$

$\theta_b = 0.08\pi$

Parameters set: Another scenario

mSUGRA values

$M_{1/2} = 250\mathrm{GeV}$ $sign(\mu) = +1$

$M_0 = 70\mathrm{GeV}$ $tan\beta = 10$

$A_0 = -300\mathrm{GeV}$

Low energy inputs

$M_1 = 100.13\mathrm{GeV}$ $\mu = 399.15\mathrm{GeV}$

$M_2 = 157.53\mathrm{GeV}$ $\tan\beta = 3.00$

$M_3 = 610\mathrm{GeV}$

$M_{A^0} = 200\mathrm{GeV}$

Neutralinos

$M\chi_1^0 = 97.62\mathrm{GeV}$

$M\chi_2^0 = 147.54\mathrm{GeV}$

$M\chi_3^0 = 405.29\mathrm{GeV}$

$M\chi_4^0 = 417.79\mathrm{GeV}$

Sleptons

$m\tilde{e}_1 = 163.22\text{GeV}$ $m\tilde{\mu}_1 = 163.19\text{GeV}$ $m\tilde{\tau}_1 = 150.07\text{GeV}$

$m\tilde{e}_2 = 187.37\text{GeV}$ $m\tilde{\mu}_2 = 187.38\text{GeV}$ $m\tilde{\tau}_2 = 190.39\text{GeV}$

$\cos\theta_e = 9.1\times10^{-5}$ $\cos\theta_\mu = 0.019$ $\cos\theta_\tau = 0.271$

$m\tilde{\nu}_e = 169.64\text{GeV}$ $m\tilde{\nu}_\mu = 169.64\text{GeV}$ $m\tilde{\nu}_\tau = 170.02\text{GeV}$

Squarks

$m\tilde{u}_1 = 506.48\text{GeV}$ $m\tilde{c}_1 = 506.47\text{GeV}$ $m\tilde{t}_1 = 345.37\text{GeV}$

$m\tilde{u}_2 = 524.14\text{GeV}$ $m\tilde{c}_2 = 524.16\text{GeV}$ $m\tilde{t}_2 = 556.78\text{GeV}$

$\cos\theta_u = 9.4\times10^{-5}$ $\cos\theta_c = 0.033$ $\cos\theta_t = 0.5567$

$m\tilde{d}_1 = 506.07\text{GeV}$ $m\tilde{s}_1 = 506.07\text{GeV}$ $m\tilde{b}_1 = 469.43\text{GeV}$

$m\tilde{d}_2 = 530.14\text{GeV}$ $m\tilde{s}_2 = 530.14\text{GeV}$ $m\tilde{b}_2 = 721.69\text{GeV}$

$\cos\theta_d = 8.5\times10^{-4}$ $\cos\theta_s = 1.6\times10^{-5}$ $\cos\theta_b = 0.9266$